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Performance Testing of the Tetradyne High Speed Air Jet Skimmer

Mason and Hanger-Silas Mason Co, Inc, Leonardo, NJ

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Industrial Environmental Research Lab -Cincinnati, Edison, NJ

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The U.S. Environmental Protection Agency evaluated the performance of the prototype Tetradyne High Speed Air Jet Skimmer at their OHMSETT test facility at Leonardo, New Jersey. The skimmer depends on an air-jet impacting the water surface at an angle and deflecting rapidly moving, floating, spilled material laterally into a low-current chamber for ease in recovery. The objective of the testing program was to determine the ability of the Tetradyne skimmer to pick up a large area, thin film (0.1-1.0 mm) spill of floating oil in water currents up to 3 m/s. The four test fluids used during the program, No. 2 fuel oil, naphtha, and two lubricating stocks, encompassed a wide range of physical properties. The recovery performance parameters determined were recovery rate and throughput efficiency. The effects of film thickness, fluid viscosity, fluid specific gravity, and fluid interfacial tension on skimmer performance parameters under fast current conditions are presented. Modifications for further improving performance are recommended.

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PERFORMANCE TESTING OF THE TETRADYNE HIGH SPEED AIR JET SKIMMER

by

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DISCLAIMER

The work described in this report was conducted under the sponsorship of the U.S. Environmental Protection Agency. This report has been reviewed by the Office of Research and Development, U.S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of these agencies, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

FOREWORD

When energy and material resources are extracted, processed, converted, and used, the related pollutional impacts on our environment and even on our health often require that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory - Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

This report describes performance testing of a research prototype, air jet, thin film, high speed oil skimmer. Based on these results, a number of design modifications are suggested. The methods, results, and techniques described are of interest to those interested in specifying, using or testing such equipment. Further information may be obtained through the Resource Extraction and Handling Division, Oil and Hazardous Materials Spills Branch, Edison, New Jersey.

David G. Stephan
Director
Industrial Environmental Research Laboratory
Cincinnati

ABSTRACT

The U.S. Environmental Protection Agency evaluated the performance of the prototype Tetradyne High Speed Air Jet Skimmer at their OHMSETT Test Facility at Leonardo, New Jersey. The skimmer depends on an air-jet impacting the water surface at an angle and deflecting rapidly moving, floating, spilled material laterally into a low-current chamber for ease in recovery. The objective of the testing program was to determine the ability of the Tetradyne skimmer to pick up a large area, thin film (0.1-1.0 mm) spill of floating oil in water currents up to 3 m/s. The four test fluids used during the program, No. 2 fuel oil, naphtha, and two lubricating stocks, encompassed a wide range of physical properties. The recovery performance parameters determined were recovery rate and throughput efficiency. The effects of film thickness, fluid viscosity, fluid specific gravity, and fluid interfacial tension on skimmer performance parameters under fast current conditions are presented. Modifications for further improving performance are recommended.

This report was submitted in fulfillment of Contract No. 68-03-0490, Job Order No. 23, by Mason & Hanger-Silas Mason Co., Inc., Leonardo, New Jersey, under the sponsorship of the United States Environmental Protection Agency. This report covers a period from May 11, 1976, to May 13, 1976, and work was completed as of December 1977.

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ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

cm	--centimetres
IFT	--interfacial tension
kg	--kilogram
kPa	--kiloPascal
kw	--kilowatt
m	--metre
m^3	--metre cubed
m/s	--metre per second
m^2/s	--metre squared per second
m^3/s	--metre cubed per second
m^3/hr	--metre cubed per hour
ml	--millilitre
mV	--millivolt
ppt	--parts per thousand
s.g.	--specific gravity
Va	--air velocity at water surface
Ve	--towing velocity
V_T	--transverse oil velocity

SYMBOLS

°C	--degrees Celsius
ϕ	--angle of air jet to water
θ	--angle of boom to skimmer centerline
β	--percent efficiency of oil movement

LIST OF CONVERSIONS

METRIC TO ENGLISH

To convert from	to	Multiply by
Celsius	degree Fahrenheit	$t_C = (t_F-32)/1.8$
joule	erg	1.000 E+07
joule	foot-pound-force	7.374 E-01
kilogram	pound-mass (lbm avoir)	2.205 E+00
metre	foot	3.281 E+00
metre	inch	3.937 E+01
$metre^2$	$foot^2$	1.076 E+01
$metre^2$	$inch^2$	1.549 E+03
$metre^3$	gallon (U.S. liquid)	2.642 E+02
$metre^3$	litre	1.000 E+03
metre/second	foot/minute	1.969 E+02
metre/second	knot	1.944 E+00
$metre^2$/second	centistoke	1.000 E+06
$metre^3$/second	$foot^3$/minute	2.119 E+03
$metre^3$/second	gallon (U.S. liquid)/minute	1.587 E+04
newton	pound-force (lbf avoir)	2.248 E-01
watt	horsepower (550 ft lbf/s)	1.341 E-03

ENGLISH TO METRIC

centistoke	$metre^2$/second	1.000 E-06
degree Fahrenheit	Celsius	$t_C = (t_F-32)/1.8$
erg	joule	1.000 E-07
foot	metre	3.048 E-01
$foot^2$	$metre^2$	9.290 E-02
foot/minute	metre/second	5.080 E-03
$foot^3$/minute	$metre^3$/second	4.719 E-04
foot-pound-force	joule	1.356 E+00
gallon (U.S. liquid)	$metre^3$	3.785 E-03
gallon (U.S. liquid)/ minute	$metre^3$/second	6.309 E-05
horsepower (550 ft lbf/s)	watt	7.457 E+02
inch	metre	2.540 E-02
$inch^2$	$metre^2$	6.452 E-04
knot (international)	metre/second	5.144 E-01
litre	$metre^3$	1.000 E-03
pound-force (lbf avoir)	newton	4.448 E+00
pound-mass (lbm avoir)	kilogram	4.535 E-01

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SECTION 1

INTRODUCTION

PREVIOUS WORK

In considering resolutions to the problem of a large-area, thin-film oil slick floating on the surface of a river, harbor, or estuary, it becomes apparent that physical removal of the oil from the surface of the water is most environmentally desirable. To collect a large-area slick in a short period of time, one may treat either a wide swath at a slow or moderate speed or a relatively narrow swath at a higher speed. Sorbent deployment and retrieval techniques have been developed by the U.S. Environmental Protection Agency to advance the state-of-the-art of slow and moderate speed technology. Hitherto, cleanup has been ineffective at high speeds where the relative velocity of the oil and water normal to the pickup or control device exceeds about 1.0 m/s. These high speed conditions are found in rivers, harbors, or open estuaries with high currents, or whenever pickup of the slick is attempted as quickly as possible by successive passes.

The speed limitation of present devices is invariably caused by their unfavorable interactions with the flow regime of oil and water moving relative to them. If efficiency at higher speeds is to be achieved, the hydrodynamic flow conditions around the device must be taken into account and, if possible, used or altered to advantage.

In 1974 the United States Environmental Protection Agency (EPA) sponsored two separate research contracts in the field of high-speed devices for the recovery of thin-film oil spills (1, 2, 4). Both projects involve deflecting oil that is moving relative to the device by means of an air jet so that the resulting oil and water spray can be captured and separated. Additionally, the U.S. Coast Guard sponsored a fast current study in 1975 (3).

The project conducted by Tetradyne Corporation of Richardson, Texas, used air jets to concentrate and, subsequently, deflect oil into a sump for gravity separation. According to their report this device achieved up to 86% (vol/vol) throughput efficiency at a speed of 1.8 m/s in towing tank tests of a full-scale prototype; it was relatively insensitive to waves, small debris, and changes in oil viscosity (1).

SCOPE

This report describes performance tests of the Tetradyne skimmer

with oil and floating hazardous materials in the EPA OHMSETT test tank facility (Appendix A). Test conditions and procedures were designed to correspond with typical inland and harbor waterways. The test fluids selected for this project were Lube oil (Sunvis 75), No. 2 fuel oil, Sunvis No. 31, Sunvis No. 7, and Naphtha, which together provided a wide range of physical properties.

SECTION 2

CONCLUSIONS

The test results indicate that the Tetradyne Air Jet skimmer needs further development to effectively recover thin film (≈0.1 mm) slicks in fast currents (2.0-3.0 m/s). Skimmer performance deteriorated in calm water with tow speeds above 1.5 m/s, and during a single test with the 0.3 m (height) harbor chop moving at 1.5 m/s, performance deteriorated until the skimmer became completely ineffective.

Previous laboratory test and tow tank test results with this skimmer were not confirmed by the tests at OHMSETT. Throughput efficiency was typically below 50% and recovery rates were below 2.3 m^3/hr, as contrasted with those previously reported by Tetradyne (4).

Possible reasons for the lower performance were:

- inadequate air supply to maintain a constant and uniform nozzle velocity > 12 m/s
- inadequate instrument and air flow controllers to measure and maintain the air flow to the booms
- inadequate oil distribution and collection techniques to accurately measure and control the rate and volume of oil laydown and removal at the end of each run.

However, despite these quantification deficiencies in thin-film testing technique, qualitative data (films, slides and observations) confirmed that even when the nozzle velocity was strong enough to cause a 0.6 m spray, the throughput efficiencies never were near the previously reported values (80%). Stronger air velocities appeared to cause both air bubble and oil droplet entrainment at the fast-current speeds. Black and white underwater video documents this gross entrainment problem. Design changes could possibly overcome this difficulty by directing the air jet more parallel to the water surface.

Tests using a variety of test fluid thicknesses did indicate a definite performance break point at about 0.2 mm. With thinner slicks, throughput efficiency was significantly higher.

Although the experimental errors were larger than normal, order-of-magnitude changes in oil viscosity and interfacial tension did seem to

affect performance significantly. As the viscosity and interfacial tension were each made larger (while the other two properties and test conditions were held constant), the throughput efficiency increased significantly. Although varying the specific gravity from 0.75 to 0.85 has no significant effect, it is felt that specific gravity above 0.85 (near 1.0) would become critical and cause excessive oil entrainment, as has been shown with other skimmers and test projects at OHMSETT (5).

SECTION 3

RECOMMENDATIONS

An optimum air jet skimmer design can only be achieved through a better understanding of the interaction of the air jet with the floating oil. Since the amount of kinetic energy transferred to the oil slick depends upon the angle of incidence of the air jet, it is doubtful that this type of skimmer would be effective in waves characterized by short periods and large amplitudes.

Further testing of this skimmer at OHMSETT is recommended, provided certain design changes are implemented. The most significant improvement would be the use of an air supply adequate to maintain an air jet velocity of at least 12 m/s. Air flow control dampers should be used to carefully control the air flow to the diverter and collector booms. Pitot tubes or other similar instrumentation should also be used to measure the air velocity in each of these booms. The optimum design would utilize controls to automatically regulate the air flow dampers, air blower, and nozzle angles in order to maintain the jet velocity. Boom angles and nozzle angles should be made easily adjustable within certain ranges above and below the optimum suggested equipment settings.

SECTION 4

DESCRIPTION OF TETRADYNE SKIMMER

The original prototype Tetradyne skimmer (1974) was damaged in transit from Texas and then rehabilitated for these tests (Figures 1, 2, and 3). The skimmer was constructed from an aluminum boat hull. The 38.1 cm wide by 40.6 cm high flow-through channel was made from aluminum sheet. This unit incorporated a false bottom with two collection chambers and utilized air flow to hold the oil in the chambers. The diverter and collector booms and nozzles were also constructed from sheet metal.

Figure 1. Tetradyne High Speed Air Jet Skimmer under test in a 0.3 m harbor chop.

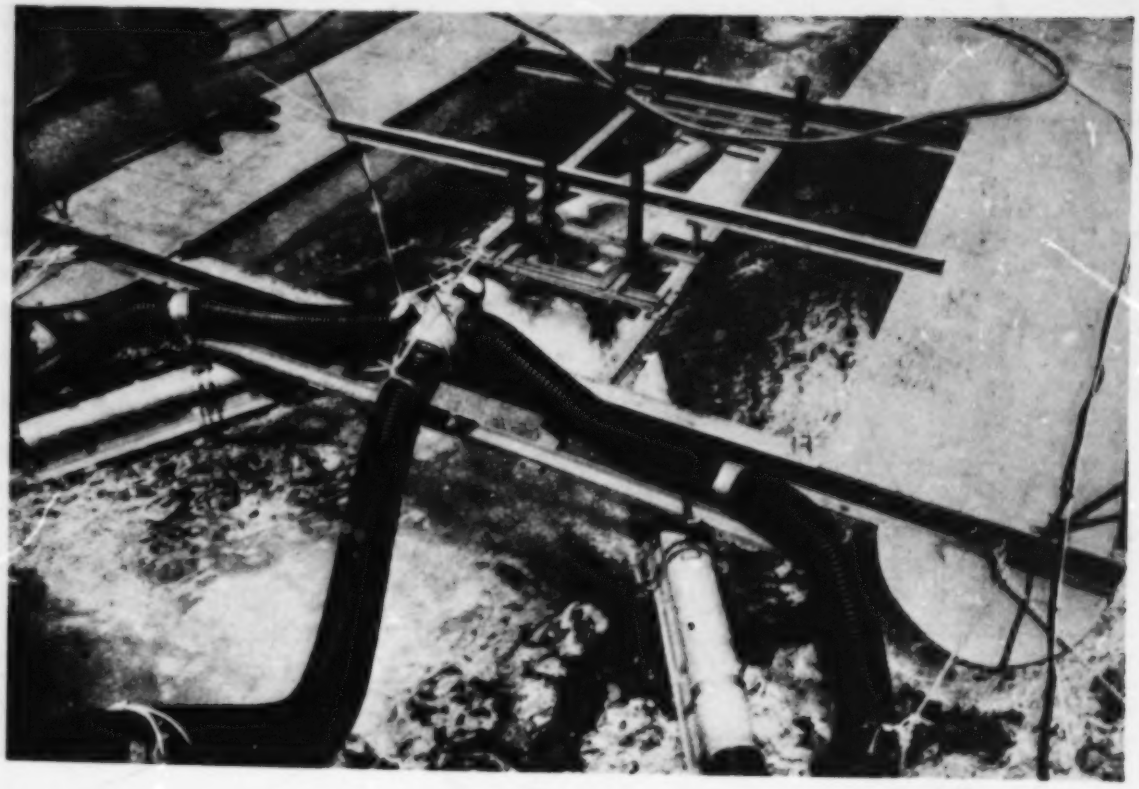

Figure 2. Tetradyne High Speed Air Jet Skimmer in calm water.

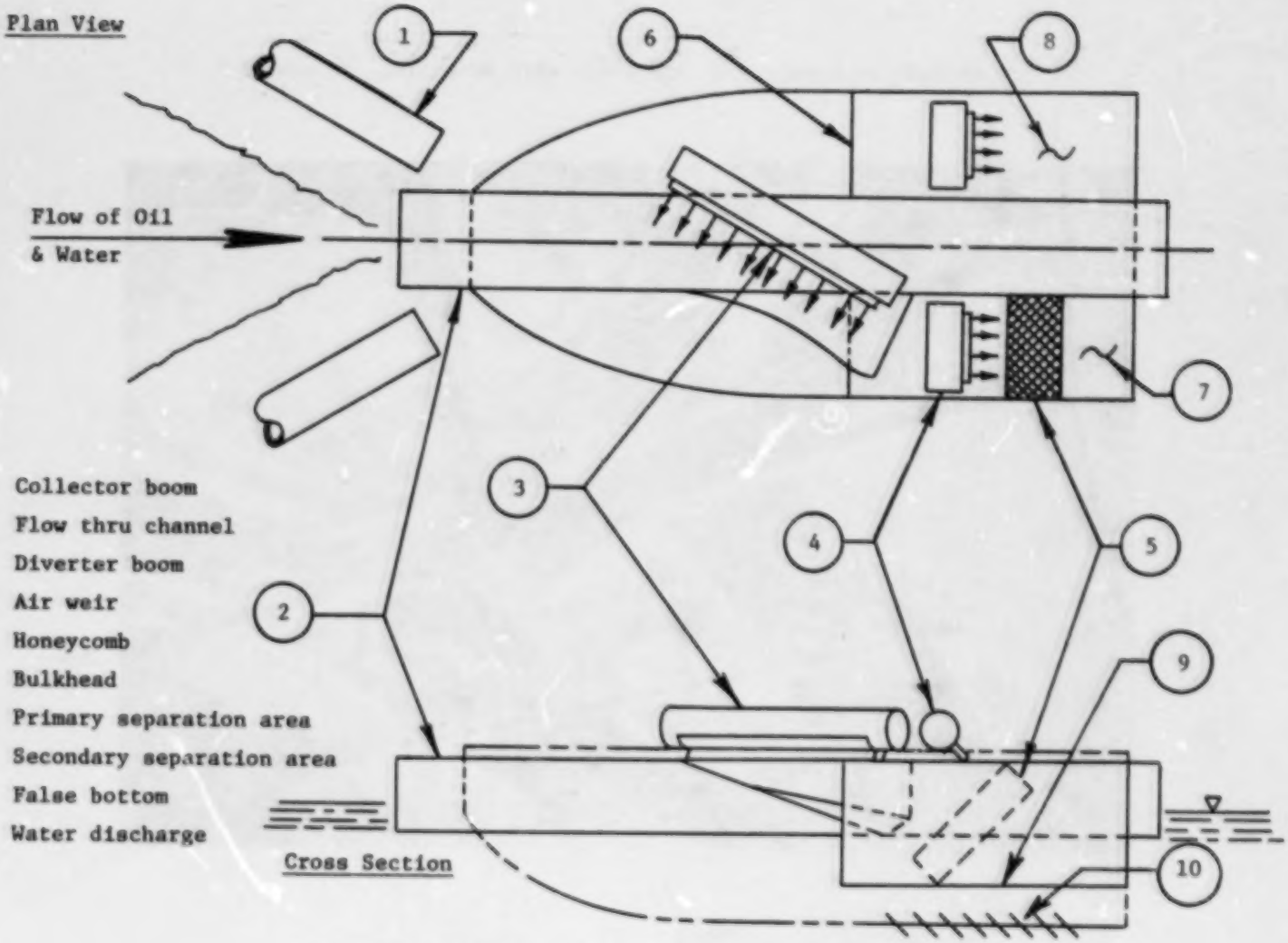

Figure 3. OHMSETT modified collector configuration.

Tetradyne's Air Jet Skimmer (1) depends on the simple principle that an air stream directed at an angle to the surface of the floating oil may be used to move the oil rapidly and horizontally across the water. If this air stream consists of an elongated air curtain, it can sweep a large area and concentrate the oil for collection. Figure 4 schematically shows the conditions which occur when air impinges on an oil/water interface with a relative velocity of 12 to 18 m/s between the boom air and the oil/water combination. This may result from the movements of the air stream, the boom itself, the water, or any combination of these relative to the earth.

Two factors help to direct the oil. First, the impinging air acts directly on the oil to move it with the air flow. Second, the surface of the water is distorted into a trough with a standing wave in front of it. This standing wave also helps to prevent the oil from passing through the air curtain. Also, a water current is generated which helps to move the oil.

Tests have shown that winds blowing horizontally across the water surface move oil at approximately two percent of the wind velocity. This relatively poor interaction is largely due to a thick boundary layer of slower moving air near the water. Tests with the air sweep system show that it causes a much stronger interaction to occur between the oil and the air stream, because the air is directed downward at the water surface, overcoming the boundary effect. Air booms have been used to hold oil directly against currents up to 0.9 m/s; however, at higher speeds an oil headwave forms and entrainment occurs.

In these tests, it was decided that 1.3 cm boom nozzles would be utilized, although the 1.9 cm nozzles would be used for larger models. This decision was based on the limited capacity of the blower and the air compressor available to supply air to the nozzles. The key parameter which had to be held constant during the tests was the air velocity at the water surface.

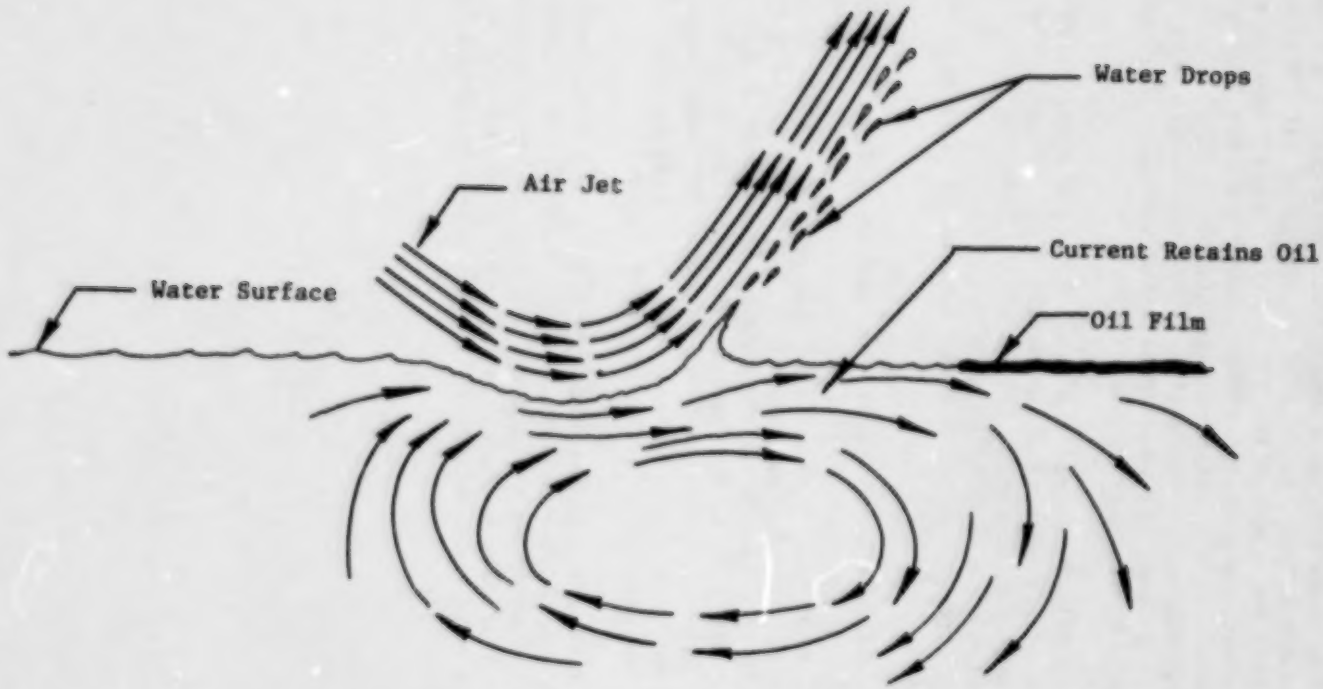

Figure 4. Air and water current interaction moving surface oil.

SECTION 5

TEST PLAN

TEST RATIONALE

For the Tetradyne skimmer, thin film oil recovery is based upon four principles:

1. A low pressure air jet directed at a 45° angle to the surface of water will move oil by means of an induced water surface current and by the surface drag of the rapidly moving air on the oil film (Figure 4).

2. A strong air jet directed onto the surface of water with a floating film of oil will "rip" the oil and some of the surface water from the main body and transport the oil and water in the form of a spray for a short but useful distance.

3. This oil/water spray can be separated by gravity.

4. The oil cannot be satisfactorily collected if it is permitted to pass through hydraulic disturbances such as bow waves or hydraulic jumps.

The above-mentioned low pressure jet (see 2) is used to herd the oil and thicken it into a windrow of chosen width. The windrow of oil is then passed into the body of the device by means of an open-top channel that has no changes in cross section, originates well ahead of the bow wave caused by the pickup unit, and passes completely through the pickup unit. The strong jet (see 2) is used to rip the windrow of oil from the surface of the water in the channel and direct it into the body of the pickup unit. The oil and water are then separated by gravity within the pickup unit.

Previous prototype testing of this device has indicated a direct relationship between performance and the following variables (see Appendix B):

1. towing velocity; Ve

2. collector boom settings; Θ, Φ, and h, the nozzle height above water

3. diverter boom settings; Θ_d, Φ_d, and h_d

4. air velocity at the water surface; Va (12.2 m/s)

Tests conducted at OHMSETT were aimed at measuring the skimmer's oil pickup capabilities with various waves, currents, and differing test fluids. First, a series of tests was designed to use a lube oil to optimize the skimmer's design parameters (including its trim) while varying film thickness, tow speed, and wave conditions. Then, the skimmer was tested with other fluids for pickup performance and dependence upon such slick properties as viscosity, specific gravity and interfacial tension.

TEST MATRIX DESIGN

Two test series were designed to accomplish the above-mentioned objectives:

1. Skimmer performance versus tow speeds (up to 3 m/s) at various film thicknesses (less than 1.0 mm) and wave conditions

2. Skimmer performance versus fluid properties such as viscosity, specific gravity (s.g.) and interfacial tension (IFT) at various tow speeds under calm water conditions.

Skimmer performance parameters were defined as follows:

Throughput efficiency (TE) - volume of oil recovered by the skimmer divided by the volume of oil actually encountered.

Oil recovery rate (ORR) - volume of oil recovered divided by test time interval during which it was recovered.

During the first series of tests (with lube oil), the following design parameters were adjusted to optimize skimmer pickup performance:

1. air flow, cfm,
2. height of nozzles above the water,
3. angle of the nozzles with respect to the water,
4. trim of the skimmer vessel under tow, and
5. length of the collector boom nozzle opening.

The test conditions for this series covered the following ranges:

1. oil thickness: 0.05 mm to 1.0 mm
2. oil slick width: 3.5 m
3. oil type: lube 100 x 10^{-6} m^2/s, 0.85 s.g., 7 x 10^{-3} N/m IFT
4. wave conditions: calm, 0.3 m harbor chop
5. tow speeds: 1.5, 2.0, 2.5, and 3.0 m/s

During the second series of tests, various fluids were used to achieve significant differences in viscosity, specific gravity, and interfacial tension of the slick. The goal was to change one of the three properties independently while holding the other two constant and

repeating the test conditions in each case; thus, the only variable affecting the skimmer performance would be the property of the specific oil. The planned and actual test fluid properties for this series are given in Tables 1 and 2.

TABLE 1. TEST FLUID PROPERTIES IN DESIGN MATRIX*

Property varied	Viscosity $\times 10^{-6} m^2/s$	Specific gravity	Interfacial tension $\times 10^{-3}$ N/m
Viscosity	10	0.85	10
	100	0.85	10
Specific Gravity	10	0.75	10
	10	0.85	10
Interfacial Tension	25	0.85	30
	25	0.85	10

*Nominal property values are listed.

TABLE 2. ACTUAL FLUID PHYSICAL PROPERTIES AT 12.8°C

Type code	Test fluid	Viscosity $\times 10^{-6} m^2/s$	Specific gravity	Interfacial tension $\times 10^{-3}$ N/m	Water content %
A	Lube oil	102.0	0.850	7.0	0.2
B	No. 2 fuel oil	7.0	0.845	5.0	0.2
C	Naphtha (low pressure)	5.0	0.780	7.0	0.2
D	Sunvis 7 oil	25.0	0.850	24.0	0.2
E	Sunvis 31/#2	25.0	0.860	5.0	0.2

The proposed test matrix is given in Table 3.

TABLE 3. PROPOSED TEST MATRIX TETRADYNE SKIMMER

Test no.	Test fluid type	Slick thickness mm	Tow speed m/s
1	A	0.1	3.0
2	A	0.5	3.0
3	A	1.0	3.0
4	A	0.1	2.5
5	A	0.5	2.5
6	A	1.0	2.5
7	A	0.1	2.0
8	A	0.5	2.0
9	A	1.0	2.0
10	A	0.1	1.5
11	A	0.5	1.5
12	A	1.0	1.5
13	B	0.1	1.5
14	B	0.1	2.5
15	C	0.1	1.5
16	C	0.1	2.5
17	D	0.5	1.5
18	D	0.5	2.5
19	E	0.5	2.5
20	E	0.5	2.5
21*	E	0.5	1.5

*Test No. 21 was conducted with 0.3 m harbor chop waves. All other tests were in calm water.

SECTION 6

TEST PROCEDURES

GENERAL TEST PROCEDURES

Prior to testing, the skimmer was deployed in the tank according to the manufacturer's recommendations. The following unique features of the Tetradyne skimmer (Figure 3) required special attention:

1. Collection boom nozzle - 1.27 cm width, 10 cm height (h) above the water, 45° angle of air jet to water (Φ), 1.8 m long, and angled horizontally 15° to the longitudinal center line of the skimmer (θ).

2. Diverter boom angled (horizontally) 45° to the longitudinal center line of the skimmer.

3. Air flow rate - air dampers were used to regulate air flow to the air jet booms to maintain $V_a \geq 12$ m/s (horizontal air velocity at the water surface).

The test device was connected by ropes between the main tow bridge and the video truss. Figure 5 schematically shows the general test arrangement and the manpower distribution.

First, air flow to the skimmer collector and diverter booms was checked. After all systems were verified as being in operation, a series of shakedown runs was performed to confirm the stability of the device when under tow. Next, performance testing began, with the surface conditions, tow speed, and oil distribution was varied in general accordance with the proposed Test Matrix (Table 3).

The tow tests were conducted in the following manner. An oil slick was laid down from the main bridge onto the water surface several feet ahead of the skimmer under tow. The device encountered the 1.5 m wide slick at various speeds from 1.5 m/s to 3.0 m/s. At the end of each test run, the recovery time and the temperature and volume of the recovered fluid were measured.

Total recovery rate was determined from the total volume of recovered oil/water mixture and the duration of the recovery time.

Samples of the oil/water mixture were analyzed in the chemistry

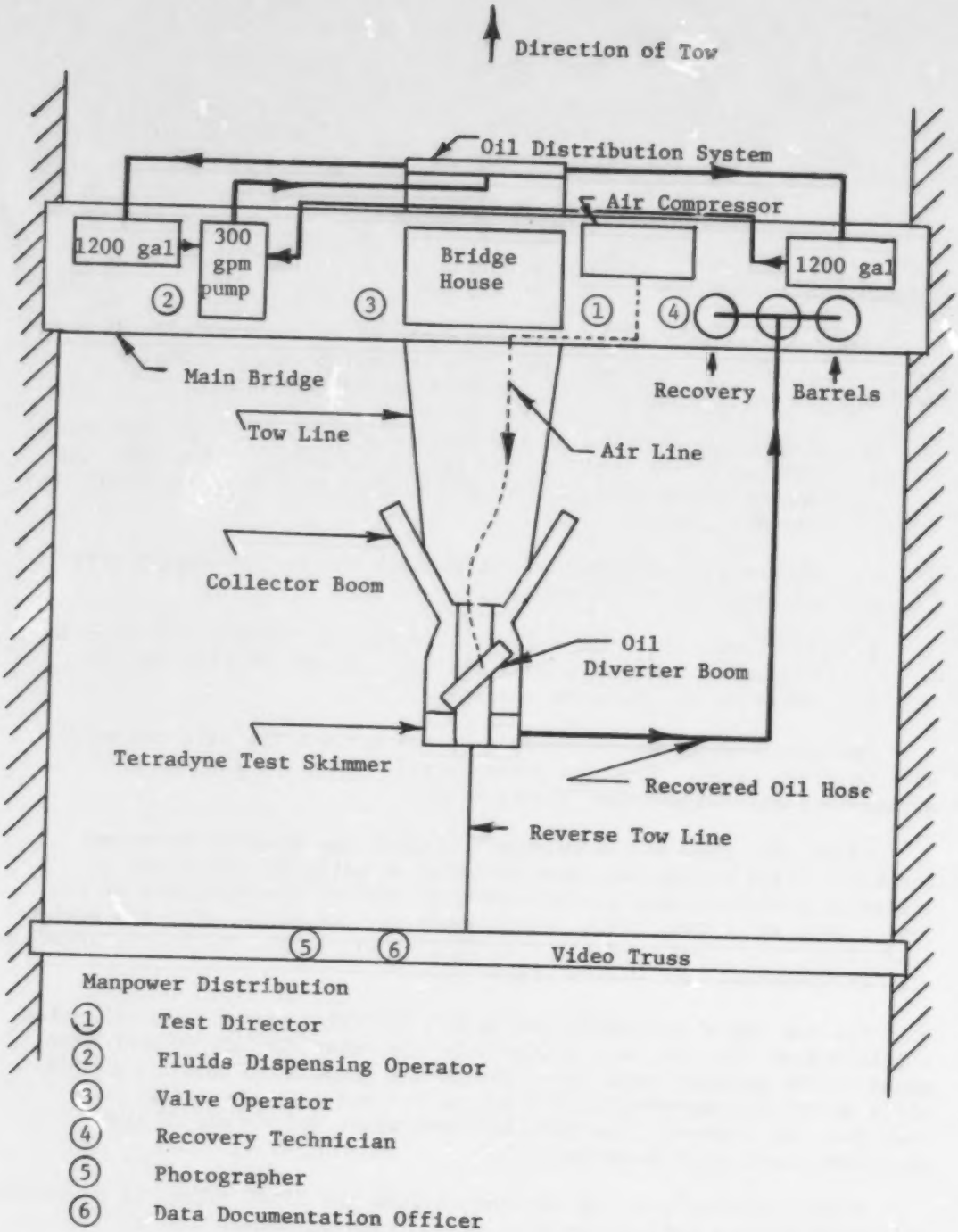

Figure 5. Sketch of Tetradyne skimmer test arrangement (plan view).

laboratory to determine accurate oil and water percentages. Oil recovery rate was calculated by multiplying the total recovery rate by the percent oil.

As is shown below, throughput efficiency was measured using total oil collected and total oil distributed (the device encountered all the test oil):

$$TE = \frac{\text{volume of oil collected}}{\text{volume of oil distributed.}}$$

MEASUREMENTS

Various measurements are made during the testing. These measurements generally include: Air--wind speed, direction, temperature; Water--temperature at the tank surface and mid-depth, specific gravity, chemical content (test fluid), wave height and length; Test fluid--temperature during the test, viscosity at that temperature, specific gravity, surface tension, interfacial tension with tank water, distribution volume, slick thickness; Recovered Material--total volume, volume of test fluid, volume of water, temperature; Time--duration of test fluid distribution, equilibrium time, total test time, various interval times; speed of the bridges; and distance traveled both during total run and at equilibrium. In addition to written records of the above measurements, 16 mm color movie and 35 mm color slide records were made of the testing. Underwater black and white videotapes were also made to record oil entrainment and flow characteristics in the oil recovery zone.

SECTION 7

RESULTS AND DISCUSSION

GENERAL

The first series of test runs concentrated on adjusting the controlled variables for optimum oil pickup at tow speeds up to 0.3 m/s and in waves. The following adjustments resulted from these tests:

1. Air flow rate was increased to the maximum by combining the compressor and blower.

2. Height of collector nozzles above the water was decreased to ≈5.1 cm.

3. Length of the collector nozzle was decreased from 2.7 m to 1.8 1.8 m.

Nozzle air velocity, V_a (from the above adjustments), resulted in observed air-impingement-spray heights equal to those documented previously (1).

4. Angle of jets to water was adjusted to ≈45°.

5. Trim of the skimmer was fixed such that the height from the top rear edge of the skimmer was ≈0.3 m above the water surface.

Wave tests were run to determine skimmer stability and response in 0.3 m and 0.6 m harbor chop waves, and in a 0.6 m x 9.1 m 3.0 sec regular wave. After several shakedown runs, each involving a different trim adjustment, it was concluded that the prototype skimmer as designed could not operate in these waves. With the air jet nozzles set at 5.1 cm of the mean (still) water level, the test waves washed up above the nozzles, submerging them and rendering the air jet ineffective. The air impingement velocity varied significantly with wave height as the nozzle height above the water surface went from zero to ≈0.6 m in the large waves tested. Only one wave test was run with oil (test No. 21); performance dropped significantly below that in an equivalent calm water test.

Recovery rates were low (maximum = 15.6 x 10^{-5} m^3/s) for the following reasons:

1. The Tetradyne device is a thin film Air Jet skimmer. Thin film skimmers are designed to recover oil slicks spread so thin that other conventional skimmers would either be unable to pickup or suffer low performance unless the oil was thickened with booms. Thin film testing requires low oil distribution rates, especially for a skimmer sweeping (i.e. for 0.1 mm slick, 1.5 m wide, traveling 3.0 m/s, the oil distribution rate was 46.7 x $10^{-5}m^3/s$).

2. Difficulty was experienced in removing the small volumes of recovered oil from the Tetradyne collection wells for measurement.

Greater air delivery capacity would definitely improve the skimmer's performance, permitting the use of longer collector booms and promoting higher recovery rates.

TOW SPEED TESTS

Throughput efficiency (the ratio of oil recovered to oil encountered) was considered the most meaningful and measurable performance parameter for this skimmer. Throughput efficiency of 100% means that the skimmer was picking up all of the oil it encountered during the test run. Performance was measured in calm water under fast current test conditions (1.5 to 3.0 m/s). As shown in Table 4 and Figure 6, throughput efficiency dropped sharply as tow speed approached 2.5 m/s and was nearly zero (within measurement accuracy) at 2.5 m/s and 3.0 m/s. It appeared that as tow speed increased, more air flow (higher nozzle velocity) was needed to offset the increased momentum of given volumes of floating oil encountering the skimmer at higher relative velocities.

SLICK THICKNESS TESTS

Since the Tetradyne skimmer was designed for thin film operations and no practical upper limit existed on slick thickness to define "thin films," tests were run to measure throughput efficiency versus slick thickness. As shown in Table 4 and Figure 7, throughput efficiency dropped sharply for slick thickness beyond 0.2 mm. Therefore, at least for this skimmer, with the low air flow rates tested, thin film-oil slicks should be defined at $\leq$ 0.2 mm thickness.

Accuracy of the slick thickness on the water surface was a matter of continuing concern during testing, especially for films < 0.2 mm thick. Inaccuracies might have been introduced in the following ways:

1. Oil volume distribution--the positive displacement flow meters used were not designed for accurate measurements below 63.1 x $10^{-5}m^3/s$. Therefore, even though volumes could be measured, accurate flow rates could not be maintained.

2. Tow Speed--periodic checks on actual versus tachometer tow speeds indicated some differences (i.e. 3.02 m/s versus 2.83

TABLE 4. TEST RESULTS TETRADYNE SKIMMER

Date	Time	Test no.	Fluid type**	Temp. °C	Ambient Conditions			Dist. rate $m^3/s \times 10^{-4}$	Slick Characteristics		% Rec.	Tow speed m/s	Rec. time s	Rec. rate $m^3/s \times 10^{-4}$	Throughput efficiency %
					Air temp °C	Wind speed m/s	Wind dir.		Slick thick mm	Slick width m					
5/11	1310	1	A	12	24.4	2.7	SSW	8.0	0.18	1.5	100	3.0	27	2.8	6.7
5/11	1334	1R	A	12	24.4	2.7	SSW	10.0	0.22	1.5	100	3.0	31	0.8	1.8
5/11	1415	4	A	12	24.4	4.5	SSW	9.2	0.24	1.5	100	2.5	37	1.1	2.6
5/11	1455	7	A	12	24.4	4.5	SSW	1.5	0.05	1.5	100	2.0	52	0.9	12.0
5/11	1515	10	A	12	24.4	4.5	SSW	3.9	0.17	1.5	100	1.5	66	3.9	11.8
5/11	1620	11	A	13	24.4	4.5	SSW	3.5	0.15	1.5	100	1.5	70	6.9	28.4
5/11	1645	11R	A	13	24.4	4.5	SSW	12.0	0.52	1.5	100	1.5	78	8.2	10.6
5/11	1725	8	A	13	24.4	4.5	SSW	20.6	0.67	1.5	100	2.0	52	9.0	7.1
5/12	1015	5	A	11.5	14.4	4.5	W	32.5	0.83	1.5	100	2.5	48	2.0	1.0
5/12	1045	5R	A	11.5	16.6	4.5	W	14.1	0.37	1.5	100	2.5	49	1.1	1.4	
5/12	1140	4	A	11.5	16.6	4.5	W	1.0	0.03	1.5	100	2.5	48	1.4	16.0
5/12	1255	3	A	11.5	16.6	4.5	W	37.9	0.98	1.5	100	2.5	48	4.2	2.8
5/12	1320	2	A	11.5	16.6	4.5	W	37.6	0.87	1.5	100	2.8	32	4.8	2.0
5/12	1345	12	A	11.5	16.6	4.5	W	19.4	0.84	1.5	100	1.5	65	12.0	12.5
5/12	1410	12R	A	11.5	16.6	4.5	W	26.4	1.13	1.5	100	1.5	69	15.6	11.9
5/12	1505	6	A	11.5	17.7	2.7	W	37.8	0.98	1.5	100	2.5	41	4.9	2.9
5/12	1600	9	A	12.0	17.7	2.7	W	37.3	0.81	1.5	100	3.0	49	2.8	2.5
5/12	1640	9R	A	12.0	17.7	2.7	W	37.8	0.81	1.5	100	3.0	49	2.8	2.5
5/13	1120	13	B	10.0	18.8	2.7	NNE	6.8	0.29	1.5	100	3.0	26	4.9	1.9
5/13	1310	13R	B	10.0	20.0	4.5	ESE	7.2	0.31	1.5	100	1.5	79	2.9	8.5
5/13	1330	14	B	10.0	20.0	4.5	ESE	8.8	0.23	1.5	100	1.5	60	4.3	9.0
5/13	1525	15	C	10.0	21.1	2.2	ESE	1.9	0.08	1.5	100	2.5	44	3.6	10.5
5/13	1550	15R	C	10.0	23.7	2.2	ESE	5.7	0.25	1.5	100	1.5	70	2.9	16.1
5/13	1625	16	C	10.0	23.9	2.2	ESE	7.7	0.20	1.5	100	1.5	52	3.3	7.0
5/13	1745	17	D	10.0	26.6	3.1	ESE	6.2	0.26	1.5	100	2.5	41	1.2	2.2
5/13	0925	17R	D	10.0	21.1	2.2	S	6.1	0.27	1.5	100	1.5	76	6.2	20.8
5/13	1010	18	D	10.0	21.1	2.7	WNW	14.3	0.37	1.5	100	1.5	67	5.3	11.6
5/13	1135	19	E	10.0	21.1	2.7	WNW	7.6	0.33	1.5	100	2.5	47	2.1	3.3
5/13	1300	19R	E	10.0	26.6	4.5	WNW	8.6	0.37	1.5	100	1.5	68	2.9	6.6
5/13	1320	20	E	10.0	26.6	4.5	WNW	15.8	0.41	1.5	100	1.5	70	2.5	5.4
5/13	1350	21*	E	10.0	26.6	4.5	WNW	10.3	0.44	1.5	100	2.5	42	1.1	1.5
												1.5	61	0.7	1.2

*Test number 21 was conducted with 0.3 m harbor chop waves. All other tests were in calm water.
**A = Sunvis 75, B = #2 Fuel Oil, C = Naphtha, D = Sunvis 7, E = Sunvis 31

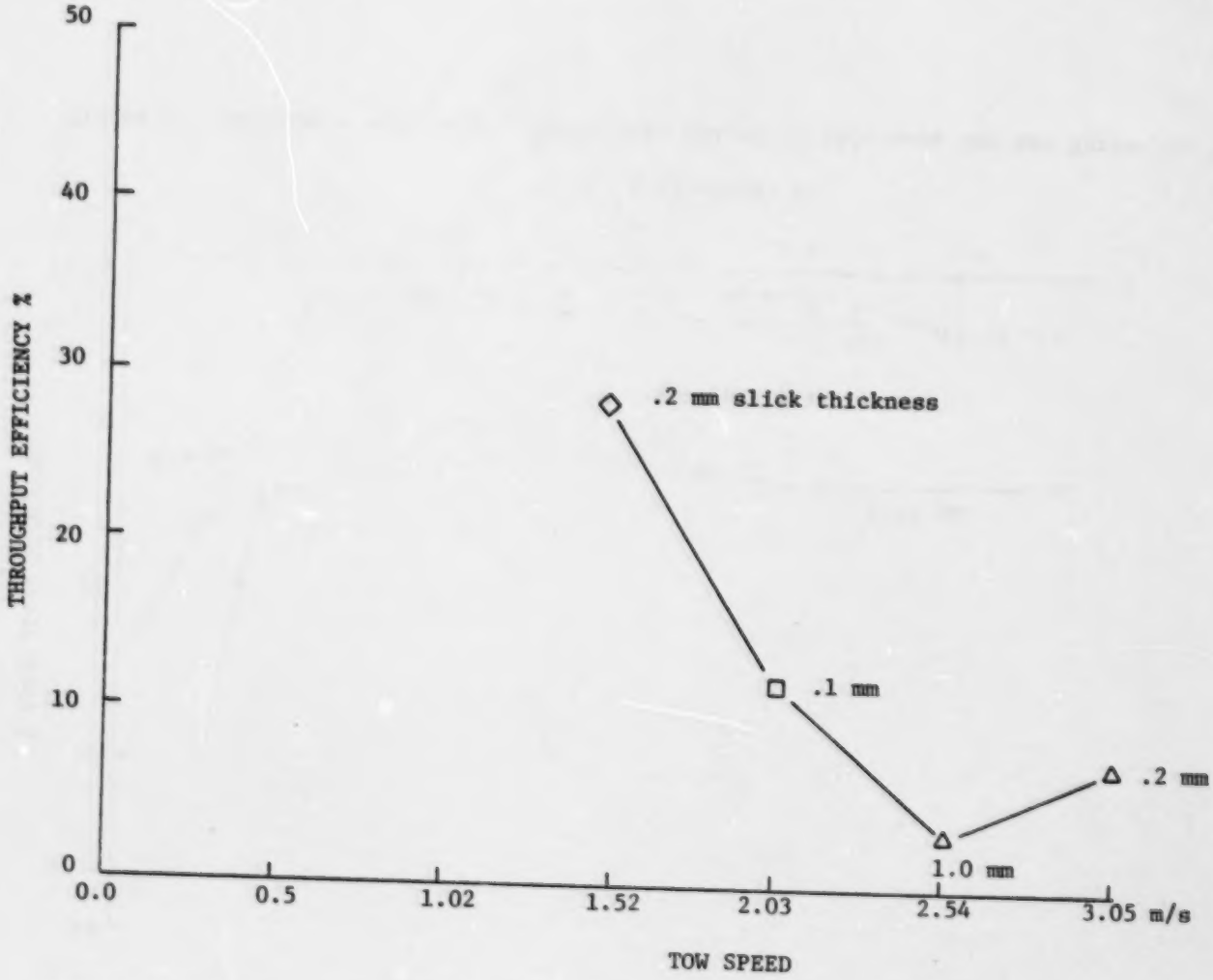

Figure 6. Maximum throughput efficiency versus tow speed for the Tetradyne Skimmer with Lube Oil.

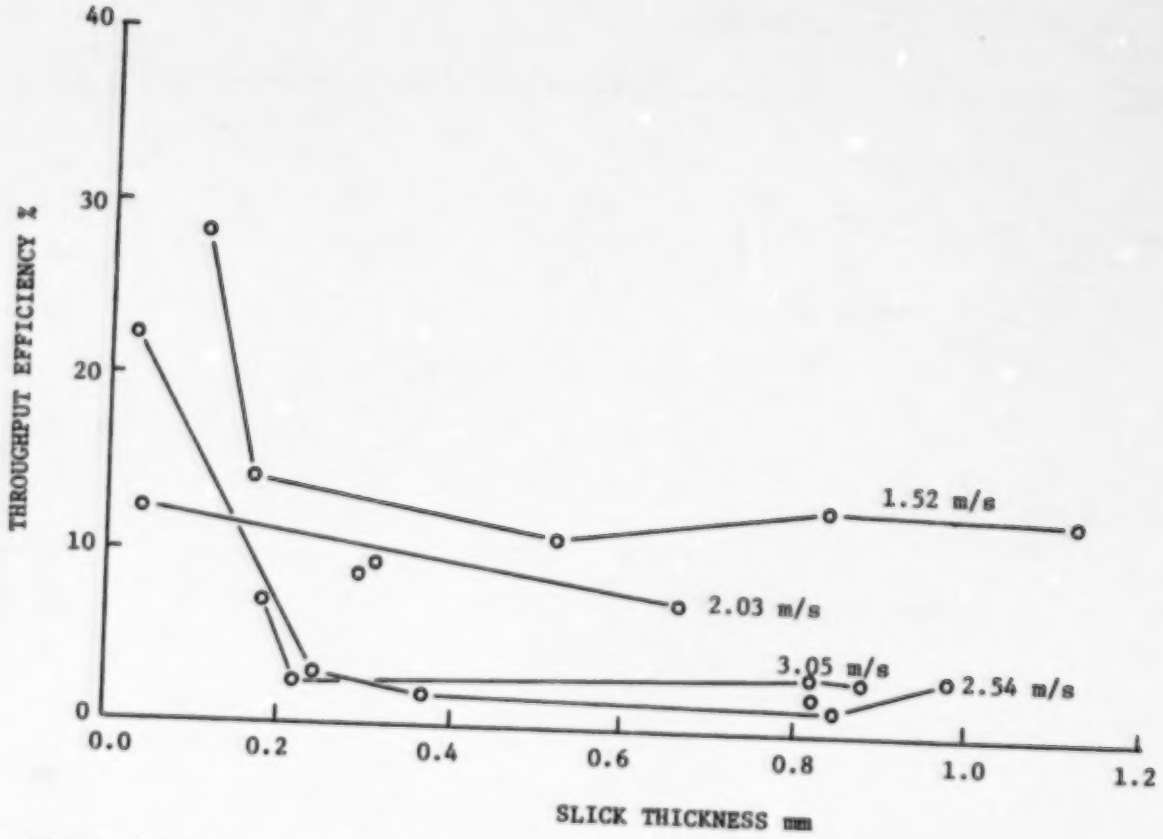

Figure 7. Throughput efficiency versus Lube Oil slick thickness for the Tetradyne Skimmer.

m/s actual for a 6.7% error).

Though these inaccuracies affect the character of the tests, performance (throughput efficiency) was measured volumetrically, independent of flow rates and film thickness inaccuracies.

OIL PROPERTIES TESTS

Skimmer performance is definitely a function of the physical properties of the oil encountered (6). Therefore, tests were run to determine the effects of specific gravity, interfacial tension, and viscosity on throughput efficiency.

Test results shown in Table 4 and Figures 8a, 8b, and 8c indicate the effects of the physical properties on throughput efficiency. The results are summarized below:

1. Specific gravity--there appeared to be no significant effect on throughput efficiencies when S.G. varied from 0.75 to 0.85.

2. Interfacial tension (between oil and sea water)--throughput efficiency increased sharply as IFT increased from 5 to 25 x 10^{-3} N/m.

3. Viscosity--throughput efficiency increased significantly as oil viscosity increased from 10 to 110 x $10^{-6}m^2/s$.

Although, not measured, the interfacial friction between the air jet and the oil would significantly effect performance. This factor depends, among other things, on the angle between the air jet and the water surface. Therefore, in rough or wavy waters, this angle could change rapidly, randomly and drastically, causing erratic skimmer performance.

MEASUREMENT ACCURACY

There are inherent difficulties in accurately measuring small volumes when conducting large scale tests. Even though 1,000-ml graduated laboratory cylinders were used when appropriate, the difficulty of removing collected oil from the secondary separation area of the skimmer caused uncertainties. A thin coating remaining on the walls might amount to as much as 1.9 x $10^{-3}m^3$, which is 5% of a typical recovery volume of 3.8 x $10^{-2}m^3$.

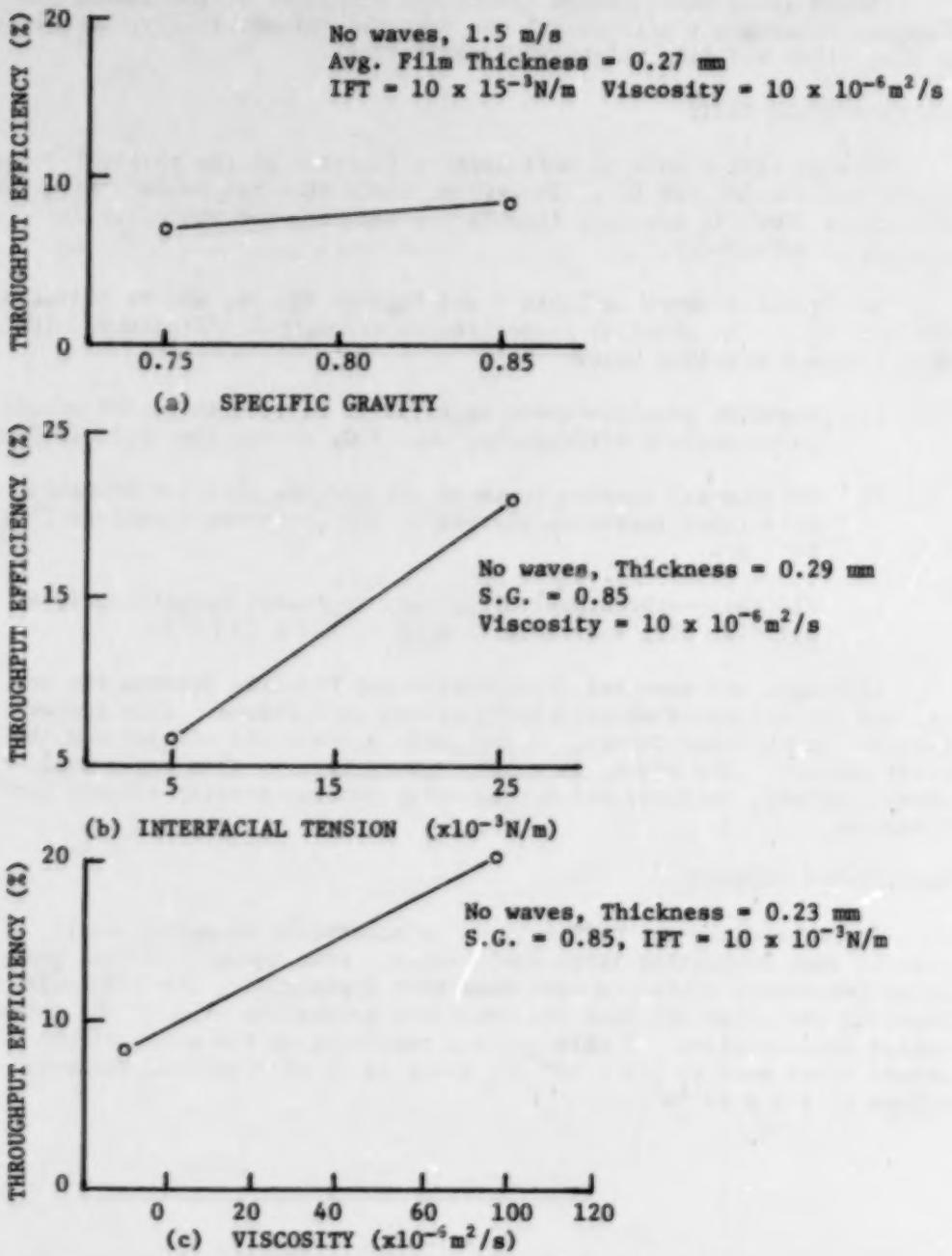

Figure 8. Tetradyne Skimmer throughput efficiency variation with changes in specific gravity, interfacial tension and viscosity. (Plotted data points are average of two test runs).

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2. Freestone, F.J., R.A. Anderson, and N.P. Trentacoste. United States Environmental Protection Agency Research in High-Speed Devices for the Recovery of Thin-Film Oil Spills. In: Proceedings, Conference on Prevention and Control of Oil Pollution. American Petroleum Institute, Washington, D.C. 1975. pp. 409-419.

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4. McCracken, W.E., and S.H. Schwartz. Performance Testing of Spill Control Devices on Floatable Hazardous Materials. EPA-600/2-77-222, U.S. Environmental Protection Agency, Cincinnati, Ohio, 1977. 139 pp.

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APPENDIX A

OHMSETT TEST FACILITY

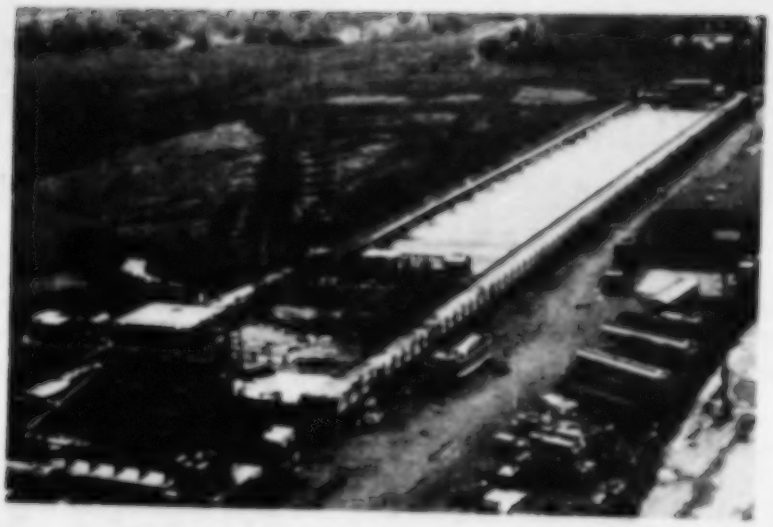

Figure A-1. OHMSETT Test Facility.

GENERAL

The U.S. Environmental Protection Agency is operating an Oil and Hazardous Materials Simulated Environmental Test Tank (OHMSETT) located in Leonardo, New Jersey (Figure A-1). This facility provides an environmentally safe place to conduct testing and development of devices and techniques for the control of oil and hazardous material spills.

The primary feature of the facility is a pile-supported, concrete tank with a water surface 203 metres long by 20 metres wide and with a water depth of 2.4 metres. The tank can be filled with fresh or salt water. The tank is spanned by a bridge capable of exerting a force up to 151 kilonewtons, towing floating equipment at speeds to 3 metres/second

for at least 45 seconds. Slower speeds yield longer test runs. The towing bridge is equipped to lay oil or hazardous materials on the surface of the water several metres ahead of the device being tested, so that reproducible thicknesses and widths of the test fluids can be achieved with minimum interference by wind.

The principal systems of the tank include a wave generator and beach, and a filter system. The wave generator and absorber beach have capabilities of producing regular waves to 0.7 metre high and to 28.0 metres long, as well as a series to 1.2 metres high reflecting, complex waves meant to simulate the water surface of a harbor or the sea. The tank water is clarified by recirculation through a 0.13 cubic metre/second diatomaceous earth filter system to permit full use of a sophisticated underwater photography and video imagery system, and to remove the hydrocarbons that enter the tank water as a result of testing. The towing bridge has a built-in skimming barrier which can move oil onto the North end of the tank for cleanup and recycling.

When the tank must be emptied for maintenance purposes, the entire water volume, of 9842 cubic metres is filtered and treated until it meets all applicable State and Federal water quality standards before being discharged. Additional specialized treatment may be used whenever hazardous materials are used for tests. One such device is a trailer-mounted carbon treatment unit for removing organic materials from the water.

Testing at the facility is served from a 650 square metres building adjacent to the tank. This building houses offices, a quality control laboratory (which is very important since test fluids and tank water are both recycled), a small machine shop, and an equipment preparation area.

This government-owned, contractor-operated facility is available for testing purposes on a cost-reimbursable basis. The operating contractor, Mason & Hanger-Silas Mason Co., Inc., provides a permanent staff of fourteen multi-disciplinary personnel. The U.S. Environmental Protection Agency provides expertise in the area of spill control technology, and overall project direction.

For additional information, contact: John S. Farlow, OHMSETT Project Officer, U.S. Environmental Protection Agency, Research and Development, IERL-Ci, Edison, New Jersey 08817, 201-321-6631.

APPENDIX B

TETRADYNE LABORATORY TESTING AND SKIMMER DESIGN DATA*

AIR NOZZLE TESTS

One of the primary factors in developing a usable air jet system involves the determination of the air velocities and volumes necessary to meet the operational requirements. Once these factors are known, it is possible to determine power and weight requirements for a skimmer vessel.

To provide the basis for the design of the air booms, nozzles and blowers, a test program was undertaken using a simulated air boom with an adjustable nozzle opening. The specific objective of this test series was to obtain data to permit selection of an optimum boom-nozzle configuration and size; to determine blower size, pressure and power requirements and determine the required boom diameters.

This test boom was positioned vertically and was supplied with air from a large blower. A Prandtl tube was mounted on a frame in front of the boom nozzle. Signals from a pressure transducer and a displacement potentiometer were fed directly to an X-Y plotter. With this arrangement, it was possible to plot a pressure profile across the air stream directly by traversing the tube in front of the nozzle. Figure B-1 is a sample of a plot for the instrument.

Using this apparatus, 172 test runs were made, testing nozzle widths of 0.6 cm, 1.3 cm, and 1.9 cm. For each of these nozzles widths, velocity profiles were prepared at distances of 0.3 cm, 15.2 cm, 0.3 m, 0.6 m, 0.9 m, 1.2 m, 1.8 m, 2.4 m, and 3.0 m from the nozzle. At each distance, six values of boom air pressure were tested to determine performance at various initial air velocities. The boom air pressures generally ranged from approximately 2.5 to 25 cm of water, although the pressure was varied in some tests to match the conditions.

One relationship which was clearly established in the test series is that the larger (1.9 cm) nozzlopening projects an air stream a significantly greater distance than the narrower nozzles. This wider nozzle also requires less pressure and power to project high velocity air over distances up to 3.05 m.

*From Reference 1 (Section III, pp. 9-19)

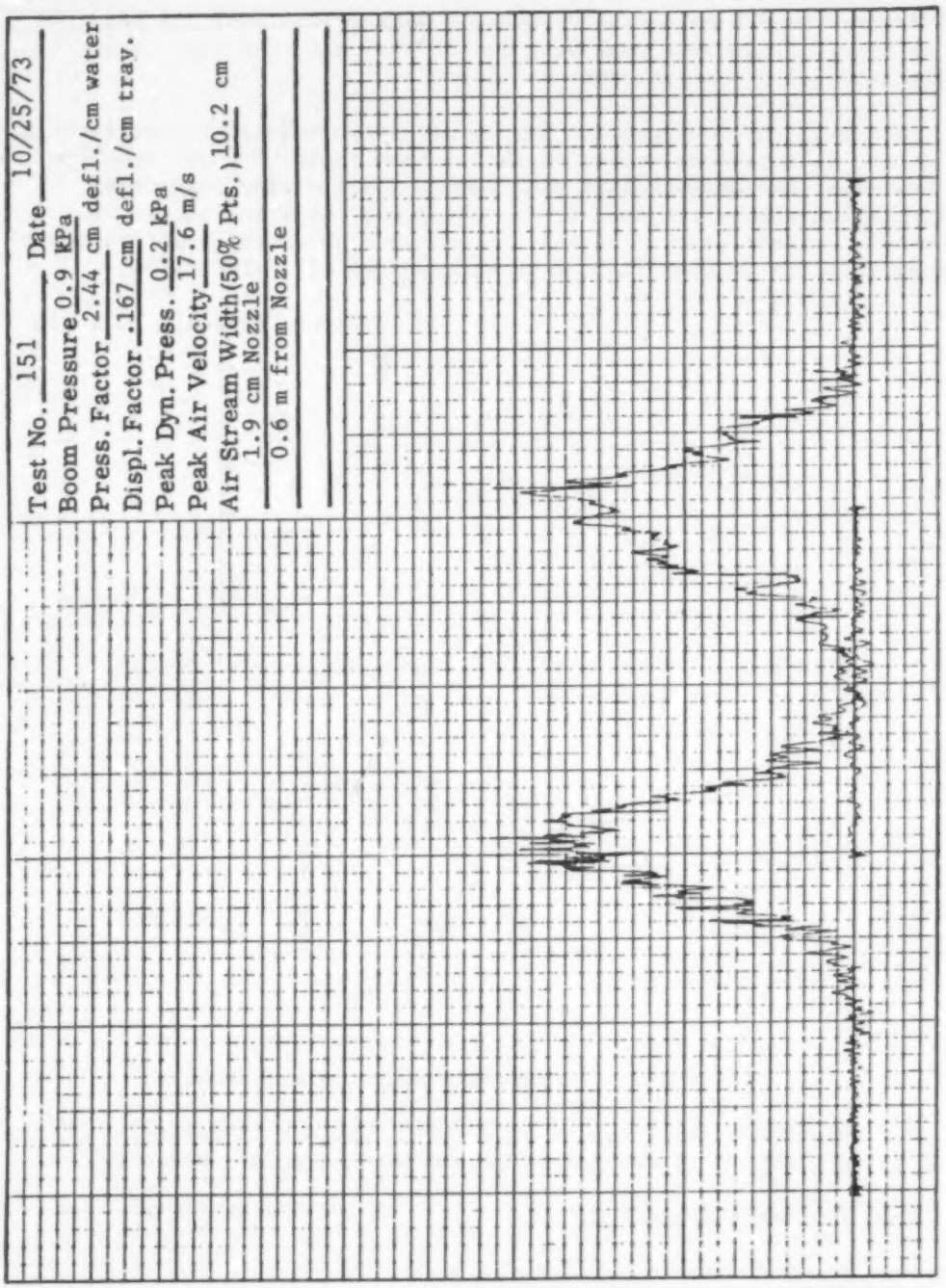
TETRADYNE CORPORATION
Test No. 151 Date 10/25/73
Boom Pressure 0.9 kPa
Press. Factor 2.44 cm defl./cm water
Displ. Factor .167 cm defl./cm trav.
Peak Dyn. Press. 0.2 kPa
Peak Air Velocity 17.6 m/s
Air Stream Width(50% Pts.) 10.2 cm
1.9 cm Nozzle
0.6 m from Nozzle
DYNAMIC PRESSURE

Figure B-1. Sample plot from X-Y plotter.

As a comparison, at 1.2 m from the nozzle and at a nozzle pressure of 1.8 kPa, the 0.6 cm nozzle produced a peak velocity of 9.1 m/s, the 1.3 cm nozzle produced a peak velocity of 11.9 m/s, and the 1.9 cm nozzle produced a peak velocity of 11.9 m/s.

Examining the requirements for an air sweep skimmer moving through the water, calculations indicated that a boom angle, $\Theta = 30°$ from the centerline of the skimmer unit will permit a 9.1 m wide collection configuration with 9.1 m long booms, while not requiring excessive transverse velocities for the oil. Figure B-2 shows the relationship of skimmer velocity to boom angle Θ and transverse oil velocity V_T.

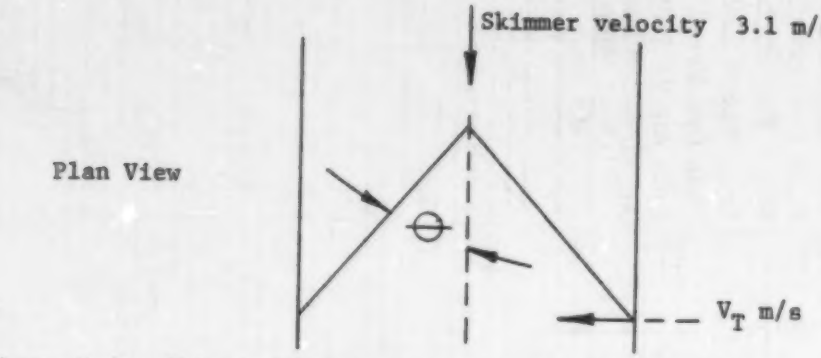

Figure B-2. Skimmer velocity--boom angle relationships.

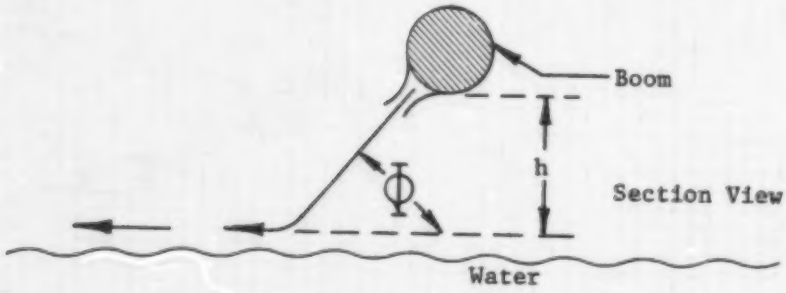

Figure B-3. Impingement angle relationships.

For relatively small values of Φ ($\simeq 50°$) the air is deflected by the water surface and V_a is assumed to be the horizontal air velocity.

From Figures B-2 and B-3.

$$V_a \text{ (Required)} = \frac{V_T}{\beta}$$

where β = % efficiency of oil movement defined as $\beta = \frac{V \text{ Oil}}{V \text{ Air}}$

One of the primary objectives of the wet tests was to measure β at various values of V_a and ϕ and at various water flow velocities.

Data from EPA tests indicate values of $\beta = .1$ for light oils moved by surface winds; however, under these conditions, the boundary layer near the water surface is large. By directing the air stream at the water surface, at the optimum angle, values of β near .2 may be reached. If $\beta = .2$ is assumed, then Figure B-4 indicates the relationship of required boom length and oil velocity for various values of Θ.

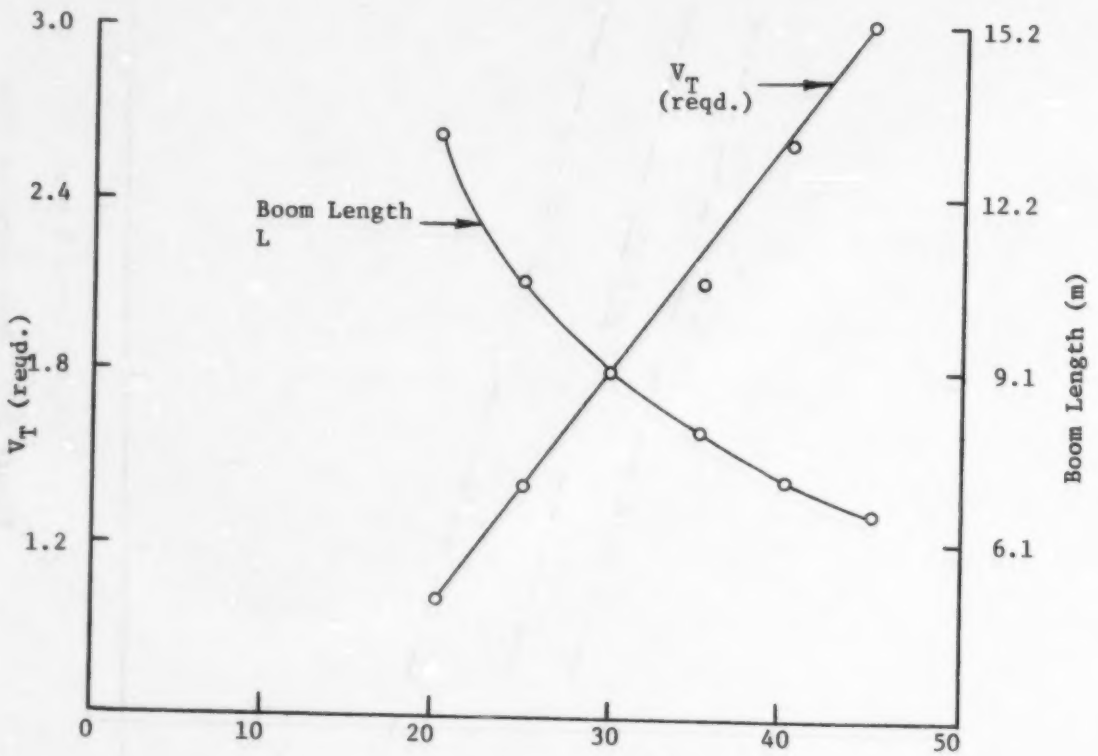

Figure B-4. Boom length and transverse oil velocity versus boom angle Θ for a 9.1 m wide sweep pattern.

Assuming $\beta = .2$, $\Theta = 30°$, and $\phi = 45°$, the required air velocity at the water surface $V_a = 12.6$ m/s. These primary estimates were to be verified in the wet tests.

Figures B-5 and B-6 are plots of test results used for preliminary system analysis. This chart compares horsepower required per 0.3-m section of boom with V_a at 1.2 m from the boom. The distance of 1.2 m

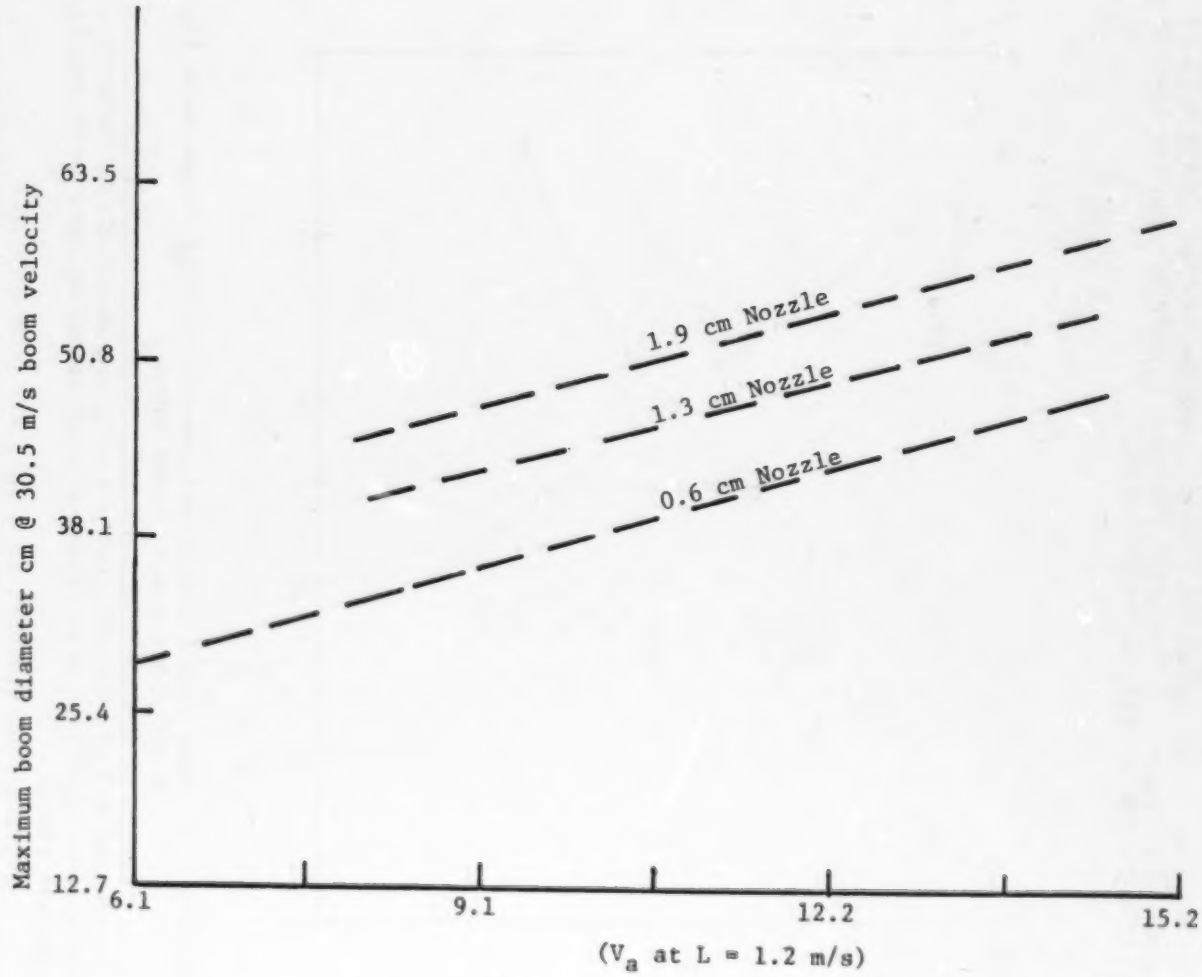

Figure B-5. Boom diameter chart.

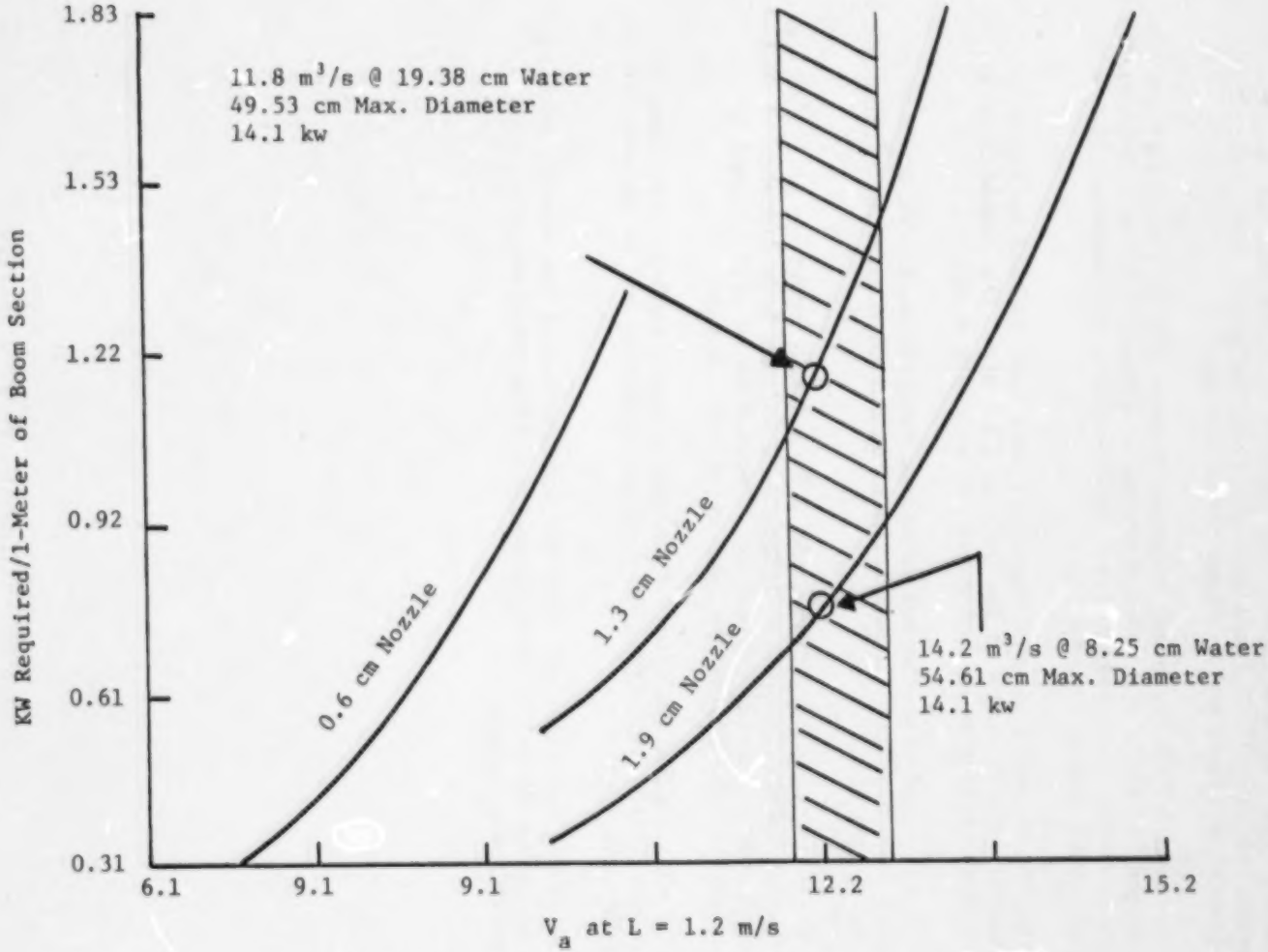

Figure B-6. Power requirement chart.

was selected as the critical distance considering wave heights of 0.6 m and values of ϕ of approximately 45°. It is clear that the larger nozzles require less pressure and power to reduce velocity at a given distance. The 0.6 cm nozzle is not capable of producing the assumed required velocity of 12.5 m/s at 1.2 m from the boom. This velocity requirement was modified by later model testing.

A trade-off decision was required between the 1.3-cm nozzle and the 1.9-cm nozzle, while the power required is greater for the 1.3-cm nozzle and it produces lower velocities. This decision was necessary prior to further model design and testing.

Curves of required boom diameters have been plotted on Figure B-5, assuming air velocity in the boom at 30.5 m/s. The shaded area in Figure B-6 represents the estimated air velocity range.

At V_a = 12.2 m/s, the 1.3-cm nozzle requires 11.8 m^3/s at 19.3 cm of water boom pressure; it indicated a maximum boom diameter of 49.5 cm and requires a total of 21.7 kw.

Under the same conditions, the 1.9-cm nozzle requires 14.2 m^3/s 8.3 cm of water boom pressure; it indicates a maximum boom diameter of 54.6 cm and requires a total of 14.1 kw. Tapered booms will be used to reduce weight and provide the best structrual support.

It was decided that the 1.9-cm nozzle has a much greater capacity to produce higher velocities at greater distances, and it appeared to be the best selection.

With the selection of these preliminary values for the air system, work proceeded on to the development of a flow table and scale models for testing the system.